Graphica Operator Interface for Space Telerobotics

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Abstract

Operator interface has recently emerged as an important element in space *telerobotics* for *efficient and safe* interactions *between the human operator and the telerobotic system. Advances in graphics and in graphical user interface (GUI)* technologies *enable development of very efficient operator interfaces. This paper addresses potential applications of advanced graphical operator interfaces* using graphics *and* graphical *user interfaces in space telerobotic* operations. *Possible applications are illustrated with examples of graphics visualization* displays *developed jor advanced teleoperation and with* an *example* of an *operator interface design developed jor remote surface inspection* at *the Jet Propulsion laboratory.*

1 Introduction

Telerobotic operations in genera] require a large number of parameter settings and monitoring capabilities, and thus a simple hardware-oriented one-sensor/one-display interface becomes inefficient, often demanding more than one highly experienced operator during the operation. Recent advances in graphics and graphical user interface (G UI) technologies enabled us to develop advanced operator interfaces using graphics displays arid/or graphical user interfaces.

Graphics displays are an important element in an advanced operator interface design, providing a means of pictorial communications between the human operator and the system. Graphics displays can be employed to achieve increased efficiency and reliability in all three phases of space telerobotic operations: in off-line task analysis and planning, in operator training, and in on-line task execution. The methodology of using graphics displays coherently in all three phases is described by examples actually developed at the JPL Advanced Teleoperation Laboratory [5]. The examples described include a new work on task analysis and planning of a simulated Solar Maximum Satellite Repair task, a force-reftectirlg teleoperation simulator for operator training [4], [7], a new graphical operator interface design for preview and on-line visualization, and predictive displays for on-line operation with time delay [1], [5].

Graphical user interface technologies [12] using graphics-oriented software such as windows, menus, and icons are also an important element in an advanced operator interface design, enabling a more sophisticated flexible operator interface in telerobotic operations for increased efficiency and safety. An example using integrated graphics and graphical user interfaces is described here with the newly developed operator interface design for a remote surface inspection system [3], [8] developed at the JPL Telerobotic Surface Inspection Laboratory with potential applications in inspecting surface damages (e. g., impacts by space debris or by micro meteorites) to space platforms such as the Space Station Freedom.

2 Graphics Visualization

Graphics displays can significantly aid the operator in accomplishing a teleoperation task in all phases of work - off-line task analysis and planning, operator training, and on-line operation. In the first phase, graphics displays provide substantial aid to investigate workcell layout, motion planning with collision detection, redundancy management, and sensor planning for camera viewing. In the second phase, graphics displays can serve as very useful tools for introductory training of operators before training them on actual hardware. In the third phase, graphics displays earl be used for previewing planned motions and monitoring oll-line operations, or, when communication time delay prevails, for providing predictive graphics overlay on the actual camera view of the remote site to show the non-time-delayed consequencies of commanded motions in real time.

2.1 Task Analysis and Planning Displays

Graphics visualization for task analysis and planning is applied to the Solar Maximum Satellite Repair (SMSR) Task [2], since one of the tasks at the JPL Advanced Teleoperation Laboratory is to perform the simulated SM SR experiments by using advanced teleoperation capabilities with dual 8-degree-of-freed om redundant (8-dof) robot arms. The SMSR task was selected, since. this task is very rich in terms of complex operational requirements and was actually performed by two EVA (extra vehicular activity - Space walk) astronauts in the Space Shuttle Payload nay in 1984. In our off-line task analysis/planning of the simulated SM SR task, the IGRIP (Interactive Graphics Robot Instruction Program) software package from Deneb Robotics is used. The package provides an excellent oJ~erator-interactive graphics simulation environment with advanced features for CAD-based model building, workcell layout, collision detection, path designation, and motion simulation.

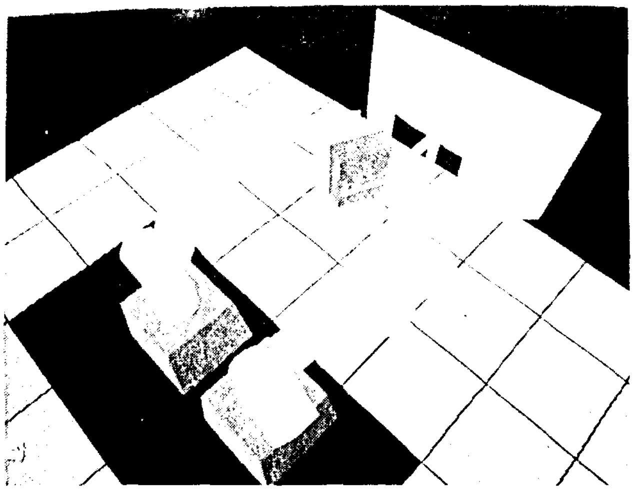


Figure 1: A graphics display of the simulated Solar Maximum Satellite Repair (SMSR) setup.

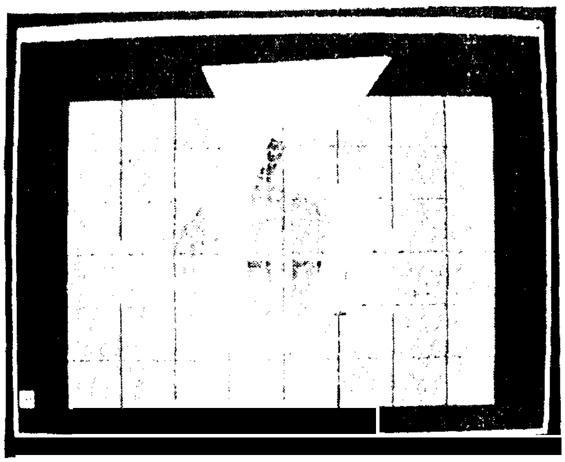


Figure 2: Workcell layout visualization with a reach envelope graphics overlay to determine the opening angle of the panel.

The workcell of the simulated SMSR task shown in a graphics display of Fig. 1 consists of two 8-dof AAI robot arms, a partial Solar Maximum satellite mockup, two "smart" hands (end effectors), a raised tile floor, arid a screw driver tool. Other workcell elements include camera gantry frame and other end effector tools such as a tape cutter. Each device in the workcell was built by first creating the individual parts of the device by using CAD-based object model building tools, and then putting them together with appropriate definitions of kinematic attributes. After all the deifiers were built, these devices were laid

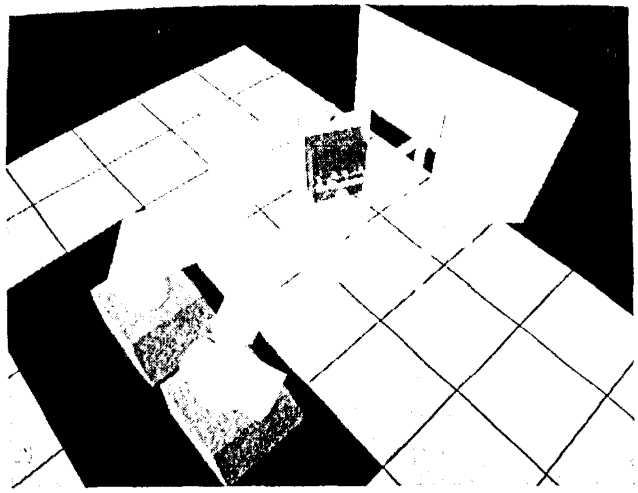


Figure 3: Graphics Visualization) for redundance management. An inadequate setting of the elbow rotation angles can cause collisions between the two arms.

out in tile workcell. In order to determine the desirable mounting locations of the robots and the satellite mockup, reach envelopes of the robots were overlaid on the workcell display for various task conditions, where each device was allowed to be moved with a mouse to satisfy the reach envelope constraints. A reach envelope visualization of Fig. 2 shows that the screw driver can reach all the screws at the right angle to the panel when the panel is open 115 degrees.

An inverse kinematic routine developed for the 8-dof redundant AAI arm [9] was incorporated into each of the two graphically simulated robot arms to allow cartesian robot control with a mouse, keyboard input, or a 6-dof hand controller. The inverse kinematic algorithm employed is an approach of fixing 2 joints and using only 6 joints at a time. At present joint 3 and 5 arc chosen as fixed joints and used as redundancy control parameters, since they arc closely related to the elbow and wrist rotations in normal operating regions of the SMSR task. In Fig. 3, the joint 3 values of the left and right arms arc inadequately set, and the elbows of the two arms are ahout to collide with each other. As the right arm moves close to its base, the two arms collide, and the parts in collision become highlighted in red. Of course, a graphic visualization in Fig. 1 shows that an adequate setting of the elbow rotation angles can avoid collisions.

Good camera viewing conditions arc essential for successful teleoperation. Simulated graphics of camera views can be used for sensor planning to determine desirable camera locations and zoom settings for each sub-task. Finally, planned motions can be verified by continuous motion simulations. A final verified planned motion for each sub-task is used later for on-line preview display.

2.2 Operator Training Displays

Recently we have developed a force-reflecting teleoperation training simulator with visual and kines-

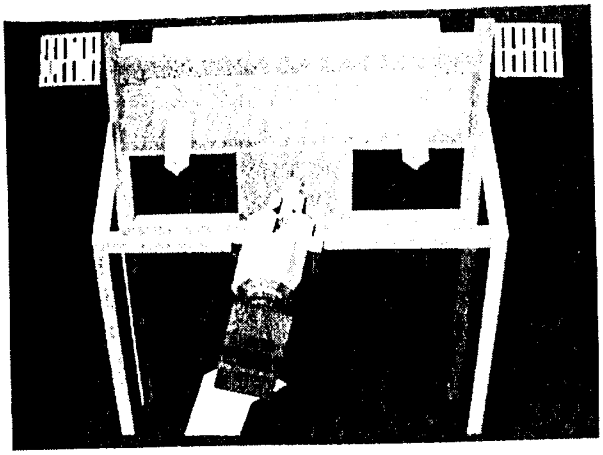


Figure 4: Force-reflecting teleoperation training displays during insertion. Contact forces and torques are computed and reflected to the force reflecting hand controller in real-time. They are also displayed on the upper left corner of the screen, while the current joint angles appear on the upper right corner.

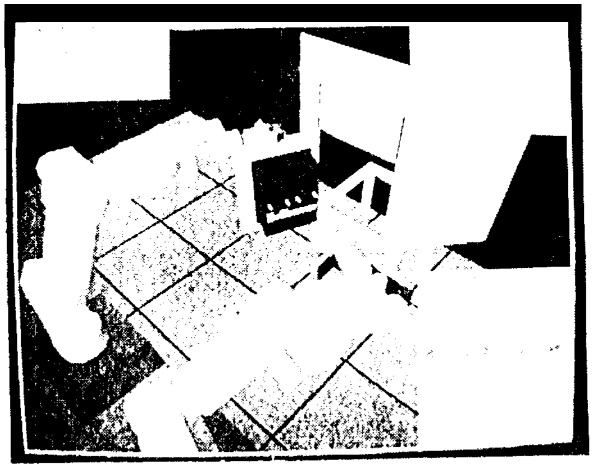


Figure 5: Graphical operator interface for preview and on-line visualization during the thermal blanket tape cutting task.

thetic force virtual reality [4], [7]. For visual virtual reality, a high fidelity real-time graphics display is used to simulate remote camera view's with three optional viewing modes: single view, two split views, and stereoscopic view. For kinesthetic force virtual reality, virtual contact forces and torques are computed during the execution of the simulated peg-in-hole task, and the operator can actually feel the virtual contact forces and torques of a compliantly controlled robot hand through a force-reflecting hand controller.

At present only a simulated peg-in-hole task can be performed with the training simulator (Fig. 4). While the operator controls the simulated PUMA arm through the 6-dof force-reflecting hand controller, virtual contact forces and torques are computed in real time and fed back to the hand controller at a data update rate of shout 15 to 30 Hz through a serial I/O line. For stereoscopic graphics display [7], Silicon Graphics StereoView is used. The operator can specify simulated force reflection gains and stiffness (compliance) values of the robot hand for the three translational and three rotational axes in Cartesian space. Testin gs with the developed peg-in-hole task simulator/trainer indicate that appropriate compliance values are essential to achieve stable force-reflecting teleoperation in performing the simulated peg-in-hole task.

2.3 Preview and On-Line Visualization

Preview displays enable operators to perceive graphics simulation of planned motion prior to sending motion commands to the remote site for actual task execution, and on-line visualization helps operators to observe and monitor actual task execution. An operator interface design example for preview and on-line visualization for use in the SMSR operations is shown in Fig. 5. An operator first selects a task from the task selection menu (lower right panel). For the task selected, the recommended joint 3 and 5 values as well as the actual joint angle values are displayed on slider bars for redundancy management (upper right panel). Prior to the actual task execution, the operator can select an option for preview (upper left panel). Four options to be available in the preview mode are teleop, auto, record, and playback. In the preview teleop mode, the operator can rehearse the task by teleoperation using graphics simulation without sending the motion commands to the remote site. During the teleop rehearsal, the operator's motion commands can also be recorded and replayed using the record and playback options. If the pre-planned motions are available through off-line task analysis/planning, the operator can use the preview auto mode to preview the pre-planned motions.

After the preview, the operator selects an option for actual task execution. Three modes to be available in the task execution mode are teleop, auto, and playback. in the teleop execution mode, the operator uses manual teleoperation for task execution. In the auto execution mode, the pre-planned motion demonstrated during the preview auto mode is actually sent to the remote site for task execution. In the playback execution mode, the recorded motion commands saved during the preview teleop rehearsal is sent to the remote site for the task execution. For free-space robot motion, the automatic execution of the pre-planned robot motion may be used with efficiency. If the task requires contacts with the environment, manual teleoperation may in general be used. The auto execution of tasks involving contacts could be also possible by incorporating the multi-sensor-based control to overcome inadvertent errors in modeling and calibrations. During the actual task execution, on-line visualization can help operators to visualize the current arm configuration at any desired angle, allowing monitoring and verification for safer teleoperation. In our system, on-line visualization graphics is updated at a 30 Hz rate by using the actual robot joint angles received.

2.4 Predictive Displays

Ground remote control of space robots draws attention recently as an interesting space telerobotics project. In this ground remote operation, however, there is an unavoidable communication time delay. In order to enhance the human operator's telemanipulation performance under time delay, we have implemented two new schemes: predictive display [1], [5] and shared compliance control [6]. Predictive display is useful during free-space robot motion, while shared compliance control is useful during contact or insertion.

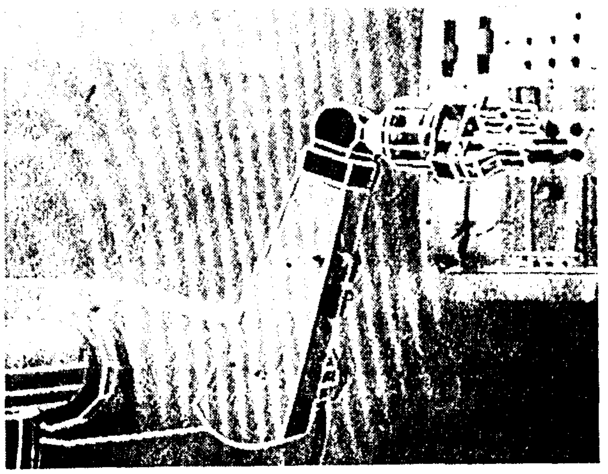


Figure 6: Calibrated graphics overlay of the wire-frame model on the actual camera view for predictive display.

In a predictive display, the graphics model is overlaid on the actual video image of the arm. The graphics model responds instantaneously to the human operater's hand controller commands, while the actual video image of the arm responds with a communication time delay. Thus the operator can see the non-time-delayed motion of the graphics model of the robot arm. While the predictive display was originally developed earlier by using a stick figure model [10], advances in graphics technologies enabled us to develop a predictive display with a high-fidelity graphics model which can be either a solid-shaded or a wire-frame model with hidden-line removal. In order to superimpose the graphics model on the video image of the arm, camera calibration was first performed by an interactive method. Both linear and nonlinear camera calibration algorithms are available. In Fig. 6, the wire-frame graphics model of the PUMA arm is superimposed on the actual camera view after the camera calibration. During the actual teleoperation under time delay, the actual video image of the arm follows the graphics model with time delay. Preliminary experiments with a single-view simple tapping task indicate that predictive display enhances the human operator's telemanipulation performance significantly, although it appears that either two-view or stereoscopic predictive displays are necessary for general 3-D tasks.

3 Operator Interface for Remote Surface inspection

A telerobotic surface inspection system [3] has been newly developed at the Jet Propulsion Laboratory to demonstrate and evaluate its capabilities for potential applications in space platforms such as the Space Station Freedom. The current JPL telerobotic inspection system uses a 7-dof Robotics Research Corporation (RRC) arm mounted on a 1-dof mobile platform. The arm carries inspection cameras, controlled lights, and other sensors for inspection and manipulation. For a simulated inspection task mockup, orbital replacement units (ORU's) are mounted on a one-third scale of a truss structure of the Space Station Freedom.

Figure 7: Operator control station housed in a realistic cupola mockup of the Space Station Freedom

The operator control station is housed in a Space Station cupola mockup (Fig. 7) to realistically simulate the equipment and operator space limitations. The operator interface hardware consists of three high resolution color video monitors, a Silicon Graphics IRIS workstation, and two 3-dof (one translational and one rotational) hand controllers that are mechanically identical to the ones used in the Space Shuttle Remote Manipulator System (RMS). The Shuttle-RMS-type hand controllers were selected to serve as a "standard" input device for teleoperated control, so that other input devices can be later compared with this standard device in terms of teleoperation performance.

The operator interface software resides in the Silicon Graphics IRIS workstation, consisting of communication interfaces to the remote-site manipulator control and image inspection systems, graphics displays, and graphical user interfaces (GUIs). The operator interface software was all written in C using the X window system, Motif widget set, Wcl widget creation library, and GL graphics library. The X window

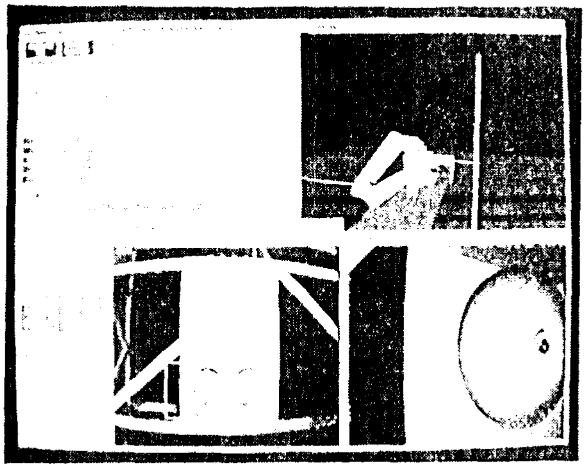


Figure 8: Top-level screen layout of the graphical operator interface for a remote surface inspection system.

system [12] is an industry standard software enabling development of '(device-independent)' portable GUI's. The interfaces are hierarchically structured by grouping similar functions together. Major and commonly used functions are presented at the top-level, and less frequently used functions are hidden in the lower levels. The top-level *screen* layout (Fig. 8) is composed of user reconfigurable multiple windows providing top-level GUI's for robot control, light control and image operations, video switch, auto sequencing, display and control sliders, automated scanning, and automated inspection.

The overall design goal of the operator interface for the JPL remote surface inspection system is to provide an efficient single-operator interface with an integrated manipulator control and image inspection capability. The interface supports three complementary inspection strategies: teleoperated (manual-scan) human visual inspection, human visual inspection with *automated scanning*, and machine-vision-based automated inspection.

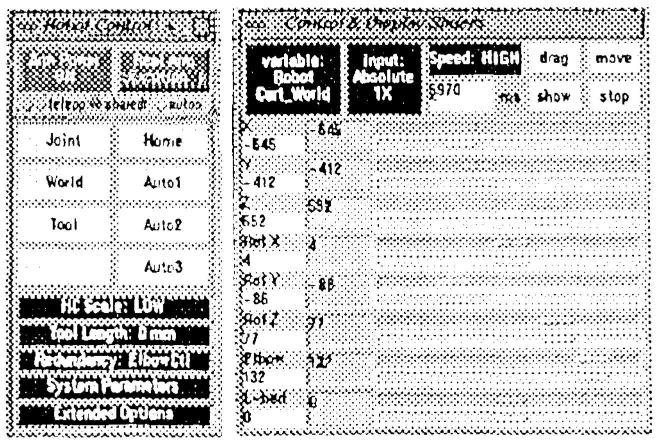
3.1 Teleoperated Human Visual Inspection

in the teleoperated human visual inspection, the operator inspects the object surface visually through video monitors, while manually scanning the surface by looking at video monitors and teleoperating the robot arm carrying inspection camera-s and controlled lights. When a flaw appears, the operator can stop scanning and capture the video image containing the flaw on the close-view window (bottom right corner in Fig. 8) of the IRIS workstation. The operator can then further examine the flaw and save the flaw image of a small rectangular region by clicking the flaw with a mouse. The operator can also mark the flaw location in the far-view image on the far-view window (next to the close-view window in Fig. 8).

In order to control the robot arm manually, the operator first sets an appropriate mode of teleoperation by using the robot control GUI (Fig. 9a). Control parameters include: 1) arm power on or off, 2) real arm drive or simulation, 3) joint, cartesian world, or *cartesian tool motion*, 4) hand controller position scale, and 5) tool length. Four auto sequence buttons (home, auto1, auto2, and auto3) are also provided for easy execution of frequently used pre-programmed or automated motions. in the shared control mode, the operator can perturb or modify the automated motion by using hand controllers.

The display and control sliders GUI (Fig. 9b) displays both the currently measured and operator-commanded robot positions. This interface allows the operator to issue an operator-commanded auto-move by specifying the robot target position and traverse time interval. The target position is specified by using either operator-commanded robot position sliders or text widgets in any one of the joint, cartesian world absolute, cartesian world relative, and cartesian tool relative modes. The traverse time interval is specified either by setting the time interval directly or, alternatively, by setting the motion speed (low, mid, high, and set).

The light control and image operations GUI (Fig. 10) allows the operator to control the light intensity levels through slider control or numerical text entry. This interface also has auto sequence buttons for image operations. The video switch GUI (Fig. 11) allows the operator to connect any output channel (typically video monitors) to any input channel (typically video cameras). The operator selects the output channel first and then the input channel. Each output channel pushbutton displays the currently connected input channel. Typically one monitor is used for surface inspection, and the other two for manipulator control.



(a) (b)

Figure 9: (a) Robot control GUI and (b) display and control sliders GUI

An extended automated sequencing capability has been developed to support both manipulation and im-

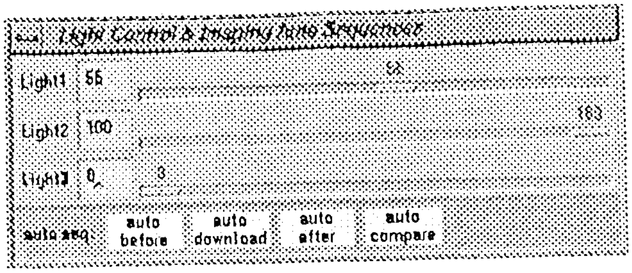


Figure 10: Light control and image operations GUI

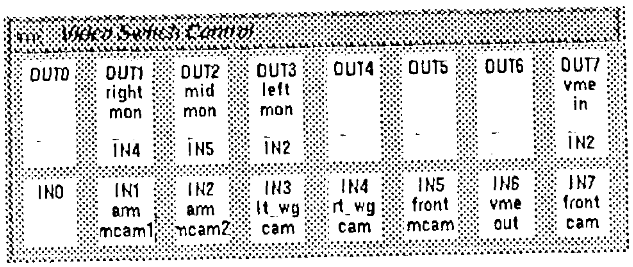
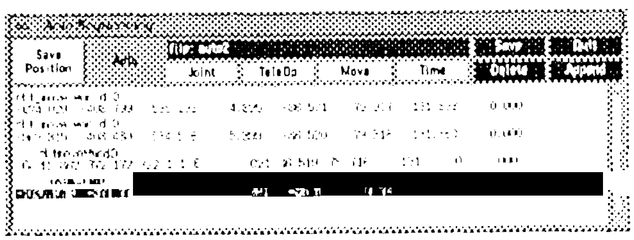
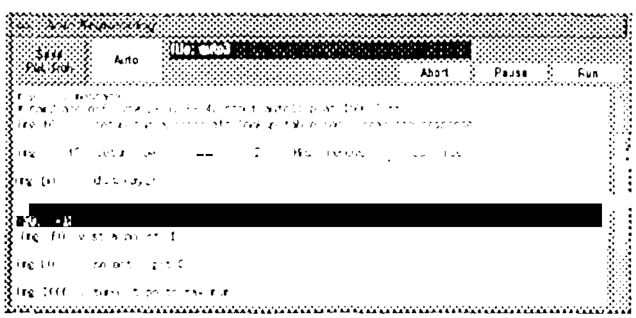


Figure 11: Video switch GUI



(a)



(b)

Figure 12: Auto sequence GUI (a) in save position mode, and (b) in auto sequence execution mode.

age inspection commands. Our implementation can be considered as an extension of the current Shuttle RMS auto sequence capability [11] which is limited to the pre-programmed robot motion control. Further, our implementation supports an interactive save-position mode, in addition to the normal auto sequence execution mode. In the save-position mode (Fig. 12a), the operator can interactively save the current arm position either in teleoperation or in operator-commanded auto move mode and generate motion commands that can be used later in writing auto sequence scripts. In the auto sequence execution mode (Fig. 12b), the auto sequence script is displayed in the scrolled list window, and the current command being executed is highlighted. The operator can interrupt the execution at any time by clicking the "pause" button, and later resume it by clicking the "run" button. The operator can also abort the remaining execution completely by clicking the "short" button. The robot motion auto sequence commands include rbt_move, rbt_pause, rbt_speed, and rbt-tool-length. The image inspection auto sequence commands include image operations (e.g., img_freeze, img_display, img_subtract), light control, and video switch commands (camera control commands will also be available).

The on-line graphics display showing the current robot arm configuration at any desired viewing angle is also provided as an effective visualization aid to the operator as described earlier in Section 2.3.

3.2 Human Visual Inspection with Automated Scanning

The automated scanning capability has been introduced to the remote surface inspection system to reduce the operator's manipulation workload and thus allow the operator to concentrate on inspection during the human visual inspection. Although a simple autoscan function is in fact available in many commercial camera pan-tilt units for surveillance, our implementation provides more sophisticated flexible automated scanning capabilities based on the automated scanning GUI supporting operator-interactive sensor planning, scan path preview, and on-line graphical visualization during the actual auto scanning.

The automated scanning procedures is conveniently divided into two phases: the sensor planning and execution phases (Fig. 13). In the sensor planning phase, the operator can register the object image and generate a scan path interactively. Currently the object surface to be inspected is assumed to be approximately a 2-D rectangular surface, although it can be extended to other surfaces such as irregular 2-D shapes or cylindrically curved surfaces. In order to register the object image and generate a scan path for a rectangular surface, the operator moves the inspection camera by teleoperation to each corner of the rectangular surface so that the video *image* of the *corner point* appears at the center of the video monitor screen (a cross hair mark at the center of the monitor screen can be helpful), while keeping the inspection camera at a desired distance from the surface. Each corner point is registered by reading the camera position and marking the corresponding corner image point in the far-view

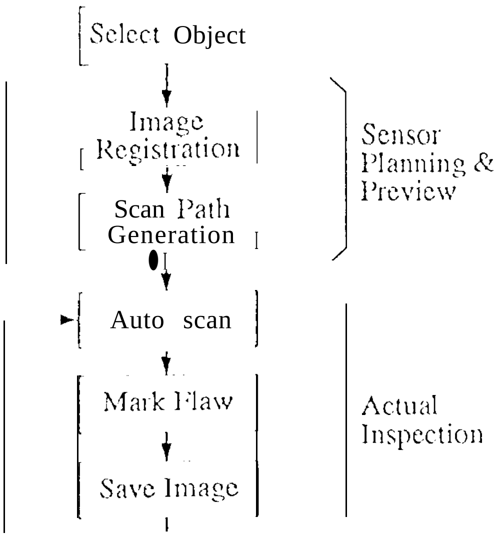


Figure 13: Schematic of the automated scanning procedures

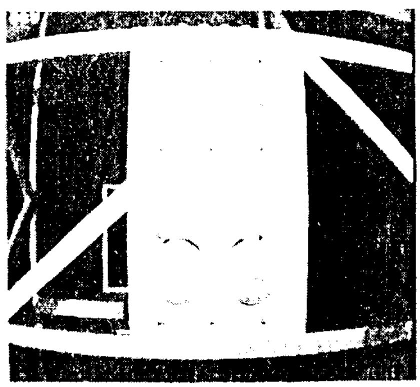


Figure 14: Automated scanning GUI with graphics overlay of a scan path and the rectangular box indicating the current camera view position and size.

window. If a far-view object image for flaw marking is not available, the far-view window simply displays a wire-frame rectangle.

After the registration, a scan path is generated so that the inspection will take place to cover the entire rectangular surface for a given camera view size. Two default scan paths are available: the horizontal path which scans the surface horizontally starting from the top row to the bottom, and the vertical path which scans the surface vertically from the left column to the right. Along the scan path, via points which defines the robot motion trajectory and vista points where automated inspection takes place are defined. The vista points are placed so that the automated inspection will cover the entire surface. All vista points are defined as via points, but additional via points are inserted to ensure smooth and accurate scanning. For effective visualization}, the scan path graphics is directly overlaid on the far-view digitized object image (Fig. 14). A rectangular box indicating the current position and the view port of the inspection camera is also overlaid to provide effective visualization to the operator.

The operator can preview and modify the generated scan path. interactively try inserting, deleting, or relocating vista and via points as needed. An example of a default horizontal scan path is shown in Fig. 14. The scan-path editing capability enables the operator to interactively generate a scan path for irregular 2-D shapes other than the rectangular shape. Once the image registration and the scan path generation are completed, the relevant image registration and scan path data are saved so that these procedures can be skipped for the subsequent inspections.

When the operator initiates scanning in the auto-scan execution phase (Fig. 13), the arm first moves to the nearest via point from the current arm position, and then follows the scan path in the specified direction which can be either forward or backward. The operator can also request the arm to go to a designated via point directly.

3.3 Machine-Vision-Based Automated Inspection

The operator's workload and inspection time can be significantly reduced by providing the operator with an automated inspection capability. By relying on the automated inspection, the operator does not have to inspect the entire surface, but examines a few portions of the inspection surface only when the automated inspection notifies the operator of a potential flaw. The operator ultimately decides whether there is a flaw on the surface. The JPL remote surface inspection system uses the machine-vision-based image differencing technique incorporated with automated scanning for automated inspection. By selecting the "reference scan" button, the operator requests the inspection system to scan the object surface along the pre-defined scan path and collect a reference or "before" image for each vista point. Then, after a period of time, the operator selects the "comparison scan" button, requesting the inspection system to re-scan the surface along the scan path identical to the one used in the reference scan. During the comparison scab, the comparison or "after" image is compared with the reference or "before" image for each vista point. To eliminate the varying ambient light effect, both the reference and comparison images are actually obtained by subtracting the image taken with the controlled light from the image with no controlled light [3].

When a large discrepancy is detected between the compensated reference and comparison images, the inspection system interrupts the automated scanning and notifies the operator of a potential flaw occurrence for further examination. First the system shows the operator the thresholded binary blob image ob-

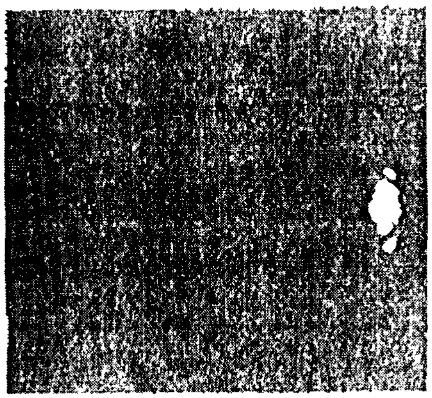


Figure 15: Automated inspection notifies the operator of a potential flaw occurrence with the thresholded binary image after image differencing. The actual flaw is the missing screw (see the graphics overlay of the flaw boundary in the close-view window of Fig. 8).

tained after the image differencing in the close-view' window (Fig. 15). When the operator hits the return key after viewing the image differencing result, the system shows the compensated comparison or "after" image on which the flaw outline graphics is overlaid (see close-view window of Fig. 8). This helps the operator to locate the flaw more quickly. The operator now examines the flaw carefully by observing various available reference and comparison images of that flaw including those from previous scans by using *an on-line flaw manipulation interface* [8]. After the careful examination, the operator can either confirm the flaw occurrence and log the flaw in a data base, or ignore it if it is a false alarm. The operator can resume the automated inspection after taking care of the flaw notification.

4 Conclusion

We described new developments and applications of graphical operator interfaces for telerobotics by employi , graphics displays and graphical user interfaces for eased efficiency and safety. We described how gra s displays were employed to achieve more efficient and reliable telerobotic operations in all three phases of off-line task analysis/planning, operator training, arid on-line operations We also described how integrated graphics and graphical user interfaces were effectively used in the new development of an efficient easy-to use graphical operator interface for a remote surface inspection system. Future plans include conducting experiments to evaluate the newly developed operator interface designs and quantify performance enhancements.

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References

[1] A. K. Bejczy, and W. S. Kim, and S. Venema, "The Phantom Robot: Predictive Displays for Teleoperation with Time Delay," IEEE Int. Conf. orr Robotics and Automation, pp. 546-551, Cincinnati, 011, May 1990.

[2] F. Cepollina and J. R. Jaax, "Extra Vehicular Activity Annex: Solar Maximum Repair Mission" JSC-14082, Annex 11, NASA Johnson Space Center, Mar. 1984.

[3] S. Hayati, H. Seraji, W. S. Kim, aucf J. Balaram, "Remote Surface Inspection for Space Applications," Proc. AIAA Aerospace Design Conf., AIAA 92-1017, Irvine, CA, Feb. 1992.

[4] W. S. Kim, "Developments of New Force Reflecting Control Schemes and an Application to a Teleoperation Training Simulator," IEEE Int. Conf. on Robotics and Automation, h'ice, France, May 1992.

[5] W. S. Kim and A. K. Bejczy, "Graphics Displays for Operator Aid in Telemanipulation," IEEE Conf. on Systems, Man, and Cybernetics, Charlottesville, VA, Ott. 1991.

[6] W. S. Kim, B. Hannaford, and A. K. Bejczy, "Force-Reflection and Snared Compliant Control in Operating Telemanipulators with Time Delay," IEEE Trans. on Robotics and Automation, vol. 8, no. 2, 1992.

[7] W. S. Kim arid P. Schenker, "A Teleoperation Training Simulator with Visual and Kinesthetic Force Virtual Reality," SPIE Conference on Human Vision, Visual Processing, and Digital Display, Society of Photo-Optical Instrumentation Engineering, San Jose, CA, Feb. 1992.

[is] W. S. Kim. K. S. Tso, and S. Hayati, "An operator Interface Design for a Telerobotic Inspection System," AIAA Aerospace Design Conference, AIAA 93-1160, Irvine, CA, Feb. 1993.

[9] S. Lee and A. K, Bejczy, "Redundant Arm Kinematics Control Based on Parameteriz ation," IEEE Int. Conf. on Robotics and Automation, pp. 458 465, Apr. 1991.

[10] M.V. Noyes and T.B. Sheridan, "A Novel Predictor for Telemanipulation Through a Time Delay," Proc. of 20th Annual Conference on Manual Control, NASA Ames Research Center, Moffett Field, CA, 1984.

[11] Shuttle Flight Operations Manual: vol. 16 - Payload Development and Retrieval System, NASA JSC, 1981.

[12] D. A. Young, *The X Window System Programming and* Applications *with Xt: OSF/Motif Edition*, Prentice Hall, 1990.